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A New Look at the Nature of Comet Halley's LF Electromagnetic Waves: Giotto Observations

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Abstract. All of the comet Halley high-time resolution magnetic field data have been examined to determine the nature of the "turbulence" and its difference from that of comets Giacobini-Zinner and Grigg-Skjellerup. Although much of the wave appears unpolarized, occasionally there are intervals of clear order. We find several interesting new wave polarizations: arc–, left-hand/arc– (sunglass) and left-hand circular polarized waves (in the spacecraft frame). The former two types have separations of -120 s between individual pulses, indicating that the waves are generated from pickup of the H_2O group cometary ions. The third type of waves occurs in a wave-train and may be a detached whistler packet. The unusual polarizations could be caused by wave refraction in the highly turbulent (and high β) Halley environment or by nonlinear evolution due to strong growth rates. It is noted that some of the large amplitude waves are non-planar. These results are further details of the "tinear polarization" of Halley waves determined by previous coherency analyses, and may explain some of the evolution leading to its plasma turbulence.

Introduction

As a comet approaches the Sun, solar heating of the nucleus leads to sublimation of atoms and molecules from its surface, leading to the creation of a vast cloud of cometary neutrals surrounding the nucleus. At a distance of -1 AU from the Sun, the combined photoionization and charge exchange time scale is -106 s. Freshly created ions constitute a ring-beam in the plasma frame, which can be unstable to the generation of cyclotron resonant electromagnetic waves. The wave mode generated depends on the pitch angle of the cometary ions relative to the interplanetary magnetic field (IMF), and thus on the orientation of the IMF relative to the solar wind flow. For IMF orientations from parallel to the $\mathbf{V}_{sw}$ direction (0°) up to 70", the right-hand magnetosonic mode is theoretically expected, while the left-hand polarized Alfvénic mode is expected for θ_{VB} = 70"-90" [*Thorne and Tsurutani*, 1987; *Brinca*, 1991; *Gary*, 1991].

Of the three comets visited by spacecraft thus far. Halley and its LF electromagnetic waves are the most complex [*Johnstone et al.*, 1987; *Glassmeier et al.*, 1989]. Although transverse power spectra indicate a peak at ~10^{-2} Hz, the H_2O group ion cyclotron frequency [*Glassmeier et al., 1987*], coherency analyses show that the wave polarization is close to linear over a broad frequency range [*Glassmeier et al.*, 1989; *Tsurutani et al.*, 1995; *Glassmeier et al.*, **1997].** Such wave polarizations have not been explained theoretically, and the HalIcy case remains a major mystery.

Coherency analyses however, make time-averaged determinations, and thus, [cave the above analyses ambiguous. Possible interpretations are: 1) the individual waves may be linearly polarized, 2) Halley waves may be composed of a mixture of right-and left-hand modes giving an average that indicates linear polarity, 3) the waves may have nonlinearly evolved from a left- or right-hand polarization to that of a phase steepened (high-frequency) wave front with a linearly polarized trailing portion.

It is the purpose of this paper to do a thorough examination of the high time resolution Giotto magnetometer data [*Neubauer, et al.*, 1986a] to determine the polarization of H_2O group ion cyclotron waves. Wave studies in other regions in space plasmas [*Goldstein and Tsurutani*, 1984; *Tsurutani et al.*, 1993; Anderson et al., 1996] have indicated that wave packets are often not uniform in polarization/direction of propagation or could be a superposition of multiple waves. We will therefore use only individual (360" phase rotation) cycles for our minimum variance wave analyses.

The data to be studied corresponds to the region upstream of the bow shock for both the inbound and outbound passes. Limiting the study to this region of space will focus on waves generated by instabilities associated with the pickup process plus further evolution. We wish to avoid contamination by shock or magnetosheath generated waves. The study represents an effort in which all of the high resolution Halley magnetic field data were reexamined to answer the question of Halley wave polarization.

Results

Wave Examples

Although much of the magnetic field data at comet Halley often appear incoherent [see *Johnstone et al.*, 1987 and Figures 5 and6 in *Glassmeier et al*, 1989; *Glassmeier et al.*, 1997], we find that there are intervals where clear quasiperiodicities arc present, It is in such regions where clues to the evolution of the LF waves may be found. Such an interval is given in Figure 1. This is reasonably typical. A comet centered coordinate system is used [*Neubauer et al.*, 1986b]. The system has the $\hat{x}$ axis pointing towards the Sun, $\hat{y}$ is in the $\hat{\Omega} \times \hat{x} / |\Omega \times \hat{x}|$ direction, and $\hat{z}$ completes the right-hand system. In the above, $\hat{\Omega}$ is the direction perpendicular to the ecliptic plane. In the Figure, sharply crested peaks can be noted in the x, y and z components at ~1716, ~1718, and ~1720 UT. These peaks are separated by ~120 s, roughly the H_2O group ion cyclotron period

Figure 1

Minimum variance analyses were performed for these intervals and for other intervals as well. A characteristic result is given in Figure 2, from March 13, 1986, 1802:25 to 1804:00 UT. In the

Figure, the 1, 2 and 3 coordinates correspond to the maximum, intermediate and minimum variance directions [*Sonnerup and Cahill,* 1967], respectively. The sequence of numbers in the top panel and also in the hodogram at the bottom have been added to allow the reader to follow the phase rotation of the wave. "B" and "E" correspond to the beginning and end of the interval, respectively.

λ_1/λ_2 and λ_2/λ_3 are the ratios of the maximum-to-intermediate and intermediate-to-minimurn eigenvalues, respectively. "eV(3)" is the minimum variance eigenvector in the comet centered coordinate system, and **B** is the interplanetary magnetic field (IMF) in the comet centered system.

The wave perturbation vector sweeps out an "arc" in the B_1 - B_2 plane. From point B (the beginning of the interval) to point 1, there is almost no phase change. From point 1 to point 2, there is a -90" rotation, from point 2 to point 3, a ~180° rotation, and from point 3 to E, another -90" rotation. Note that from point 1 to E, a 32 s interval, the phase rotation is almost a full 360". The sharpest rotation occurs from points 2 to 3, a -2 s interval where -180" rotation in phase occurs. Thus the rotation in phase is not uniform over time, but at times it is much more rapid. The peak-to-peak perturbation variation is -8 nT, indicating $|\Delta \mathbf{B}|/|\mathbf{B}| > 1.0$, a highly nonlinear wave,

Similar arc-polarized waves have been reported for interplanetary Alfvén waves and rotational discontinuities [*Tsurutani et al.*, *1994, 1996*]. The rotational discontinuities are the phase steepened fronts of the long period nonlinear Alfvén waves. Since the interplanetary Alfvén waves are noncompressive, the waves arc spherical in nature (the wave perturbation vector rotate on the surface of a sphere). Arc-polarization is the large amplitude analog of linearly polarization for the small amplitude case

In Figure 2, the wave $\mathbf{k}_3$ direction relative to the ambient magnetic field is 55", where $\mathbf{k}_3$ is the direction of minimum variance. The large angle that $\mathbf{k}_3$ makes to **B** is typical of the waves analyzed at Halley. The overall range of θ_{k_3B} in the study was 0° to -70". *Tsurutani et al.* [1997], however, have indicated there may be a problem in assuming that $\mathbf{k}_3$ is the wave direction of propagation for arc-polarized waves.

A field magnitude decrease is present at the edge of the wave. At 1803:24-:46 UT the field magnitude was -7,0 nT and at 1803: 53-:60 UT, it was -5.7 nT, a decrease of 1.3 nT or -20%. This could be evidence of moderate decompression at the leading edge of the wave. It should be noted that this compression is not always present. Some of the wave cycles in Figure 1 had little or no accompanying compression, and are probably the more typical case, The noncompressive case would correspond to spherical waves.

Figure 3 is an example of a wave cycle that was detected on the outbound trajectory. The format is the same as in Figure 2. Points B, I through 5, and E, are indicated in both the minimum variance component plots and the hodogram. The wave polarization is somewhat similar to the previous arc-polarization shown in Figure 2, but has a more "loopy" structure, The

[Figure 3]

magnetic field direction is out of the Figure, so it is noted that the wave has a left-hand polarization in the spacecraft frame. The hodogram has the shape of a pair of "sunglasses".

The wave in Figure 3 is propagating at -7' relative to the ambient magnetic field. Such small angles are relatively rare. However, when cases are found, the waves are typically left-hand elliptically or linearly polarized (in the spacecraft frame), This polarization is consistent with anomalous Doppler-shifted right-hand waves excited by pick-up cometary ions.

Figure 4a is an example of a wave packet consisting of 4 cycles of -11 s waves, Their transverse amplitudes are moderate, 2 nT peak-to-peak in a 4.7 nT field, $\Delta B/|B| \cong 0.4$. The hodograms for all of the wave cycles were quite similar. We therefore show only a single cycle for the interval 1108:03-:12 UT (Figure 4). In the Figure, the magnetic field is oriented out of the plane of the paper. The wave is left-hand circularly polarized in the spacecraft frame. The other cycles are left-handed as well (not shown). The direction of propagation is 15° relative to the ambient magnetic field. The large λ_2/λ_3 eigenvalue ratio of 13.4 indicates that the wave is quite planar, We finally note that there is a lack of proton cyclotron wave detection, consistent with the results of *Mazelle and Neubauer* [1993]. *Lakhina and Verheest* [1995] have given some theoretical possibilities for this omission.

Figure 4

IMF Directionality

The IMF orientation relative to the solar wind velocity (taken as the antisolar direction) in all four Figures shown previously is less than 70" (31", 47", 30" and 25", respectively). Thus, one theoretically expects the generation of right-hand resonant (magnetosonic) waves during these intervals (Thorne and Tsurutani, 1987). Such waves would be propagating towards the Sun, but because their phase velocity is typically far less than the solar wind speed, they would be convected past the spacecraft and detected as left-hand polarized in the spacecraft frame. This is the first time such waves have been demonstrated at comet Halley.

Discussion

We have shown some interesting comet Halley LF electromagnetic wave polarizations in Figures 1-3, both "arc-polarizations" and "left-hand/arc polarizations". Recent theoretical analyses by *Lee and Parks* [1995] which indicate the possibility of phase steepening of large amplitude Alfvén waves with the development of elliptical polarizations, may apply to the above cometary observations,

Another theoretical approach is to consider soliton development of cometary waves after their initial excitation. *Mjølhus and Hada* [1997] have been able to replicate the features of the Giacobini-Zinner magnetosonic wave plus whistler packet by applying the Derivative Nonlinear Schroedinger (DNLS) equation. They have assumed quasi-parallel, weakly-non[incar and weakly-dispersive MHD waves. Although these conditions are not exactly those of the data, the close correspondence is impressive. *Mjølhus and Hada* [1 997] also note "banana polarizations" (their figure 2a), which have been interpreted by the authors as an obliquely propagating, weakly dispersive shear Alfvén wave. This polarization is between the "arc" and the "sunglass" polarizations discussed here.

Sunglass-shaped polarizations result from the consideration of oblique two-parameter solitons [Figure 12 in *Mjølhus and Hada*, 1997]. Those wave hodograms contain a "cusp" but are not as flattened as those in the Halley data. An example of a stationary DNLS solution [Figure 2 of *Hada et al.*, [989] is noted to be similar to that of Figure 3 in this paper. Thus, it appears that several different soliton solutions look similar to the wave forms at Halley.

One fundamental question is "what is the relationship between spherical arc-polarized waves and the nonplanar sunglass-shaped polarizations?" For the initial solar wind conditions where the IMF is <70° relative to V_{sw}, we expect to have the generation of right-hand (circular) polarized magnetosonic waves from the ion ring-beam instability due to the pickup of the cometary heavy (H_2O group) ions. These waves would be detected as left-hand polarized in the spacecraft frame. Further, due to the highly dispersive plasma (high β), and large fluctuations in density, rapid wave refraction should occur with wave polarization evolution towards arc-polarization (the nonlinear analog of linear polarization). Thus, the sunglass-type polarization may be an evolutionary step towards the arc-like state.

The left-hand polarized (spacecraft frame) packet of waves shown in Figure 4 are consistent with their being anomalously Doppler-shifted whistler mode waves. *Coates et al* [1990] indicate a beta of -2.8 at Halley just outside the bow shock, not including the pickup ions. With the pickup ions included, the β was 11.7. Due to the higher β at comet Halley (for G-Z, researchers have assumed β was -I-2 [not including heavy ions]), this far greater dispersion at Halley could allow whistlers to detach and quickly propagate away from the magnetosonic wave. Further analysis will be needed to test this hypothesis.

We have presented some new results which explain some of the detailed characteristics of comet Halley's "linearly polarized waves" [*Glassmeier et al.* 1989]. Parallel theoretical work has been quite helpful in interpreting the observations, although it is obvious that further efforts are needed on both sides for better understanding,

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References

Anderson, B. J., R. E. Denton, and S. A. Fuselier, On determining polarization characteristics of ion cyclotron wave magnetic field fluctuations, J. *Geophys. Res /0/,* 13195, 1996.

Brinca, A. L.. Cometary linear instabilities: From profusion to prospective, in *Cometary Plasma Processes*, ed. by A. John stone, Am. Geophys Univ. Press, Washington, D. C., 6/. 216, 1991.

Coates, A. J., A. D. Johnstone, R. L. Kessel, D. E Huddleston, B. Wilkes, K. Jockers and F. M Neubauer, Plasma parameters near the comet Halley bow shock, *J. Geophys. Res., 95,* 20701, 1990.

Gary, S. P., Electromagnetic ion/ion instabilities and their consequences in space plasma: A review. *Space Sci Rev.*, 56, 373, 1991.

Glassmeier, K.-H., F. M. Neubauer, M. H. Acuna, and F. Mariani, Low-frequency magnetic field fluctuations in comet P/Halley's magnetosheath: Giotto observations, *Astron. Astrophys., 187,* 65, 1987.

Glassmeier, K.-H., A J. Coates, M. H. Acuna, M. L. Goldstein, A. D. Johnstone, F. M. Neubauer and H. Reme, Spectral characteristics of low-frequency plasma turbulence upstream of comet P/Halley, *J. Geophys. Res.*, 94, 37, 1989,

Glassmeier, K.-H., B. T. Tsurutani and F. M. Neubauer, Adventures in parameter space: A comparison of low-frequency waves at Comets, in *Nonlinear Waves and Chins in Space Plasmas*, ed T. Hada and H. Matsumoto, Term Sci. Publ. Co., Tokyo, Japan, p. 77, 1997.

Goldstein, B. E., and B. T. Tsurutani, Wave normal directions of chorus near the equatorial source region, *J. Geophys. Res.*, 89, 2789, 1984.

Hada, T.. C. F. Kennel, B. Buti, Stationary Nonlinear Alfvén Waves and Solitons, *J. Geophys. Res.*, 94, 65, 1989.

Johnstone, A., K. Glassmeier, M. Acuna, H. Borg, D. Bryant, A. Coates, V. Formisano, J. Heath, F. Mariani, G. Musmann, F. Neubauer, M. Thomsen, B. Wilken, and J. Winningham, Waves in the magnetic field and solar wind flow outside the bow shock at comet P/Halley, *Astron. Astrophys., 187,47,* 1987.

Lakhina, G. S. and F. Verheest, Pickup proton cyclotron turbulence at comet P/Halley, *J. Geophys. Res.. 100,* 3449, 1995.

Lee, N. C. and G. K. Parks, Hydromagnetic discontinuities from the evolution of nonlinear Alfvén waves, *Geophys. Res. Lett.*, 22, 1477, 1995.

Mazelle, C. and F. M. Neubauer, Discrete wave packets at the proton cyclotron frequency at comet P/Halley, *Geophys. Res Lett.*, 20, 15.7. 1993.

Mjølhus, E and T. Hada, Soliton theory of quasi-parallel MHD waves, in *Nonlinear Waves and Chaos in Space Plasmas* ed. by T. Hada and H Matsumoto, Terra Sci Publ. Co., Tokyo, Japan, p. 121.1997.

Neubauer, F. M et al., The magnetometer investigation onboard Giotto, *Eur. Space Ag.. 1077,* 1, 1986a

Neubauer, F. M., K -H. Glassmeier, M. Pohl, J. Roederer, M. H. Acuna, L F. Burlaga, N. F. Ness, G. Musmann, F. Mariani, M K. Wallis, E. Ungstrup, H. U. Schmidt, First results from the Giotto magnetometer at Comet Halley. *Nature, 321,* 352, 1986b.

Sonnerup, B, U, C), and L, J. Cahill, Jr., Magnetopause structure and altitude from Explorer 12 observations, *J. Geophys. Res.*, 72, 121, 1967.

Thorne, R. M. and B. T. Tsurutani, Resonant interactions between cometary ions and low frequency electromagnetic waves. *Planet. Spore Sci., 35,* 1501, 1987,

Tsurutani, B. T , R. M. Thorne, E J Smith, J. T. Gosling and H. Matsumoto, Steepened magnetosonic waves at comet Giacobini-Zinner, *J Geophys Res* 92. 11074, 19U7.

Tsurutani, B. T.. D. J. Southwood, E J. Smith, and A Balogh, A survey of low-frequency waves at Jupiter. The Ulysses encounter. *J. Geophys. Res 98,* 2 I 203, I 993

Tsurutani, B T , C M tin. E J. Smith, M. Neugebauer, B. E Goldstein, J S. Mok, J. K. Arballo, A Balogh, D. J. Southwood and W. C

Feldman, The relationship between interplanetary discontinuities and Alfvén waves, *Geophys. Rec. Lett., 21,* 2267, 1994.

Tsurutani, B. T., K.-H. Glassmeier, F. M. Neubauer, An intercomparison of plasma turbulence at three comets: Grigg-Skjellerup, Giacobini - Zinner and Halley, *Geophys. Res. Lett.*, 22, 1149. 199S.

Tsurutani, B. T., C.M. Ho, J.K. Arballo, E.J. Smith, B.E. Goldstein, M. Neugebauer, A. Balogh, W.C. Feldman, Interplanetary discontinuities and Alfvén waves at high heliographic latitudes: Ulysses, *J. Geophys. Res., 101,* 11027, 1996.

Tsurutani, B. T., C.M. Ho., J.K. Arballo, G.S. Lakhina, K.-H. Glassmeier, and F.M. Neubauer, Nonlinear electromagnetic waves and spherical arc-polarized waves in space plasmas, *Plasma Phys Control Fus., 39,* A237, 1997.

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Figure Captions

Figure 1. An example of the irregular Halley H_2O group ion cyclotron waves. Sharp temporal changes in the field components can be noted at -1716, ~1718 and ~1720 UT. The quasiperiod is -120s. There is only small compressional component associated with the fluctuations.

Figure 2. A Halley LF wave in minimum variance coordinates. The hodogram at the bottom indicates that the highly nonlinear wave is "arc-polarized". Most of the phase rotation occurs at the trailing portion of the interval, between points 2 and 3.

Figure 3. Another example of a Halley wave. The polarization is left-handed in the spacecraft frame and has some properties similar to "arc-polarization". The wave is phase-steepened and nonplanar.

Figure 4. a) An example of a "high frequency " (~11 s) wave train at comet Halley. b) A hodogram of one of the wave cycles of Figure 4a. The wave is left-hand circularly polarized in the spacecraft frame.

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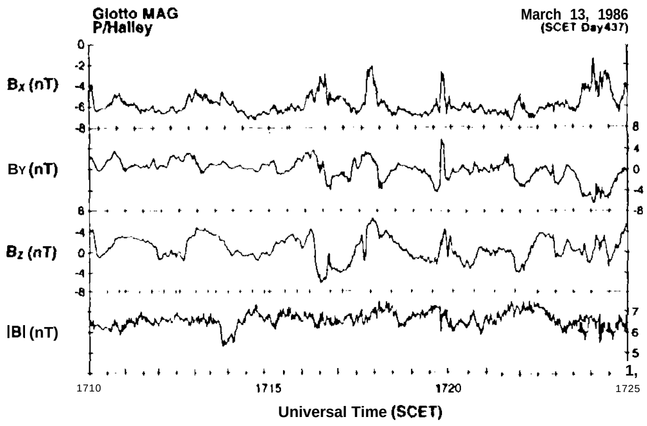
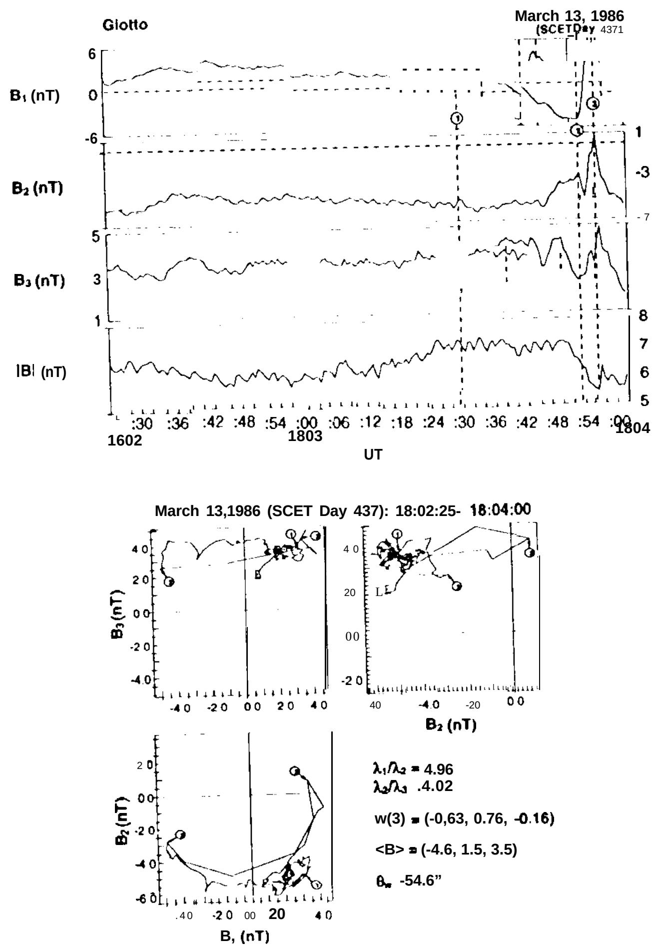

Giotto MAG
P/Halley
March 13, 1986
(SCET Day437)
Bx (nT)
By (nT)
Bz (nT)
|B| (nT)
1710
1715
1720
1725
Universal Time (SCET)

Fig. 1



Glotto
March 13, 1986
(SCET Day 437)
B₁ (nT)
B₂ (nT)
B₃ (nT)
|B| (nT)
:30 :36 :42 :48 :54 :00 :06 :12 :18 :24 :30 :36 :42 :48 :54 :00
1602
1803
1804
UT
March 13,1986 (SCET Day 437): 18:02:25- 18:04:00
B₃ (nT)
B₂ (nT)
B₁ (nT)
λ_1/λ_2 = 4.96
λ_2/λ_3 .4.02
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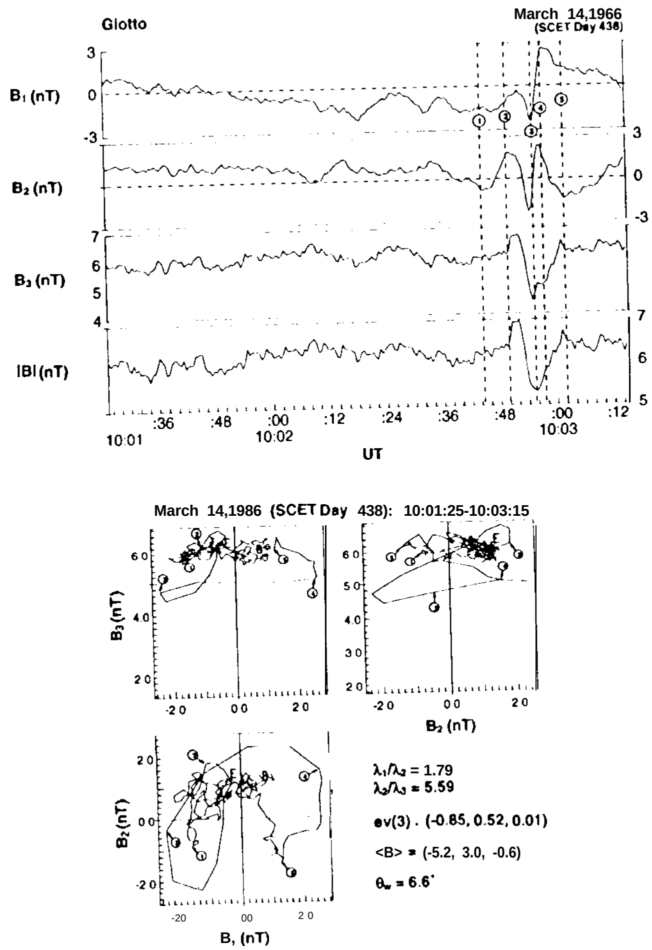
<B> = (-4.6, 1.5, 3.5)
θ_w -54.6"

Fig 2


Giotto
March 14,1966
(SCET Day 438)
B1 (nT)
B2 (nT)
B3 (nT)
|B| (nT)
10:01
10:02
10:03
UT
March 14,1986 (SCET Day 438): 10:01:25-10:03:15
B3 (nT)
B2 (nT)
B1 (nT)
λ1/λ2 = 1.79
λ2/λ3 = 5.59
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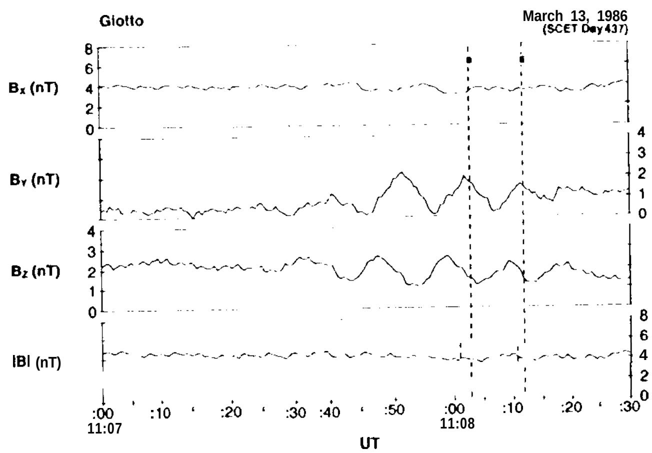
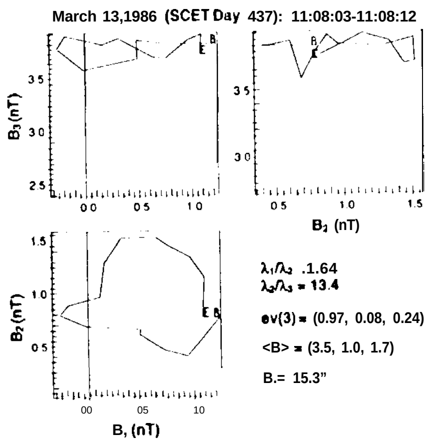
θw = 6.6°

Fig 3



Giotto
March 13, 1986
(SCET Day 437)
B_X (nT)
B_Y (nT)
B_Z (nT)
|B| (nT)
:00
11:07
:10
:20
:30
:40
:50
:00
11:08
:10
:20
:30
UT



March 13,1986 (SCET Day 437): 11:08:03-11:08:12
B_3 (nT)
B_2 (nT)
B_1 (nT)
λ_1/λ_2 .1.64
λ_2/λ_3 = 13.4
ev(3) = (0.97, 0.08, 0.24)
<B> = (3.5, 1.0, 1.7)
B.= 15.3"

Fig 4